NUMERICAL STUDY ON ENGINEERING ASPECT OF THE CELL GEOMETRIES AND FLOW CHANNEL DESIGN OF VANADIUM REDOX FLOW BATTERY (V-RFB)

SUHAILAH BINTI SUJALI

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

____

(Supervisor's Signature)

Full Name : TS. DR. MOHD RUSLLIM MOHAMED

Position : ASSOCIATE PROFESSOR

Date :

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : SUHAILAH BINTI SUJALI

ID Number : MEE 16002

Date :

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ABSTRAK

Tesis ini membentangkan ciri-ciri hidrodinamika Vanadium redok bateri teralir (V-RFB) dengan menggunakan model dinamik cecair pengkomputeran 3D (CFD) untuk mengkaji daya pam (penggunaan tenaga pam) dan pengagihan aliran elektrolit yang diperlukan dalam sel. Kuasa pengepaman dan aliran elektrolit yang sekata merupakan diantara faktor yang mempengaruhi prestasi sel V-RFB. Antara lainnya, CFD dikenali sebagai salah satu cara untuk mengkaji ciri-ciri hidrodinamika V-RFB. Dalam tesis ini, tiga geometri sel berbeza dari sel V-RFB, iaitu reka bentuk sel persegi, rombus dan bulat dikaji pada tiga kes yang berlainan iaitu tiada saluran (kosong) saluran, saluran selari dan saluran serpentin. Selain itu, kerja telah diperluaskan dengan timbunan modular 100 cm^2 V-RFB. Timbunan sel telah dibangunkan dan diuji untuk memerhatikan kuasa pam dalam timbunan pada tiga reka bentuk yang secara langsung berkait dengan prestasi sel berkenaan dengan pengagihan kuasa dan kehilangan kuasa. Berdasarkan penemuan ini, sel mempamerkan ciri-ciri yang berbeza di bawah V-RFB sel geometri berlainan tanpa penggunaan saluran aliran. Sebaliknya, berdasarkan skala geometri sel, hubungan antara kuasa pam dan geometri sel untuk 100 cm^2 V-RFB telah dibangunkan. Pengagihan aliran optimum dalam sel tanpa saluran aliran bendalir telah direkodkan; penggunaan pam tertinggi dan terendah masing-masing pada 25.6% dan 18.4%. Pengurangan kerugian kuasa sebanyak 53% telah dicatatkan dengan penggunaan saluran aliran selari yang digunakan untuk V-RFB. Hubungan berkala diperhatikan untuk modular V-RFB sebagai hasil penambahan sel dan berpotensi untuk analisa yang akan datang pada lanjutan ke sel-n seterusnya. Kerja-kerja selanjutnya dikemukakan untuk kajian masa depan dalam kajian geometri V-RFB.

ABSTRACT

This thesis presents the hydrodynamics behavior of the Vanadium redox flow battery (V-RFB) by using 3D computational fluid dynamics (CFD) models to study the pump power (pump energy consumption) and electrolyte flow distribution required within the cell. Pumping power and uniformity electrolyte flow are known as among the factors affecting a V-RFB cell performance. Among others, CFD is recognized as one of methods to study hydrodynamic characteristics of V-RFB. In this thesis, three different cell geometries of V-RFB cell, namely square-, rhombus- and circular cell designs are evaluated at three different cases i.e. no flow (plain) channel, parallel channel and serpentine channel. Furthermore, the work has been extended in modular stack of 100 cm^2 of V-RFB. The stack has been developed and tested to observe the pump power within the stack in the three designs which directly related to performance of the cell with respect to power distribution and power losses. Based on the findings, the cell exhibits different characteristics under different geometries of V-RFB cell at no flow channel application. Conversely, based on the scaling up of the cell geometry, the relationship between pump power and cell geometry for 100 cm^2 of V-RFB has been developed. Optimum flow distribution within the cells without fluid flow channels were recorded; highest and lowest pump consumption at 25.6% and 18.4% respectively. Extended reduction of power losses by 53 % were recorded as parallel flow channels was applied to the V-RFB. Proportionate correlations were observed for modular V-RFB as a result of scaling up of the cell and potential for further analysis of extension to the n^{th}-cell. Further works are presented for future research in geometry study of V-RFB.

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LIST OF SYMBOLS

Aec	Area of electrode with distribution channel, mm^2
Kck	Carman kozeny-constant
ρ	Density of electrode, kg/m^3
μ	Dynamic viscosity, kg/ms
E^0	Equilibrium potential
F	Faraday constant
ν	Kinematic viscosity, m^2/s
Lec	Length of flow channel, mm
Vin	Mean Velocity, m/s
df	Mean fibre diameter, μm
M	Molar mass of reactant, cm/s
ε	Porosity of electrode, ι
ΔPa	Pressure drop, KPa
K	Permeability of porous media
Re	Reynolds number
Av	Specific surface area, mm
θ	Thickness of electrode, mm
C	Vanadium concentration, mol/m^3
Q	Volumetric flow rates, cm^3s^{-1}

LIST OF ABBREVIATIONS

BES	Battery Energy Storage
CAES	Compressed Air Energy Storage
CFB	Circular Flow Battery
CFD	Computational Fluid Dynamics
DC	Direct Current
ECESS	Electrochemical Energy Storage System
EESS	Electrical Energy Storage System
EV	Electric Vehicle
Fe-Cr	Iron Chromium
FESS	Flywheel Energy Storage System
HEV	Hydrogen Evolution Reaction
MESS	Mechanical Energy Storage System
PHES	Pumped Hydro Energy Storage
RES	Renewable Energy
RFB	Redox Flow Battery
SHE	Standard Hydrogen Electrode
SIMPLE	Semi Implicit Method of Pressure-Linked Equation
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
UNSW	University of New South Wales
V-RFB	Vanadium Redox Flow Battery
VRLA	Valve Regulated Lead Acid

REFERENCES

Aaron, D. S., Liu, Q., Tang, Z., Grim, G. M., Papandrew, A. B., Turhan, A., … Mench, M. M. (2012). Dramatic performance gains in vanadium redox flow batteries through modified cell architecture. *Journal of Power Sources, 206*, 450–453. https://doi.org/10.1016/j.jpowsour.2011.12.026

Alamri, B. R., & Alamri, A. R. (2009). Technical Review of Energy Storage Technologies when Integrated with Intermittent Renewable Energy. *2009 International Conference on Sustainable Power Generation and Supply*, 1–5. https://doi.org/10.1109/SUPERGEN.2009.5348055

Alotto, P., Guarnieri, M., & Moro, F. (2014). Redox fl ow batteries for the storage of renewable energy : A review, Renewable and Sustainable energy reviews, *29*, 325–335. https://doi.org/10.1016/j.rser.2013.08.001

Alotto, P., Guarnieri, M., Moro, F., & Stella, A. (2012). Redox Flow Batteries for large scale energy storage. *2012 IEEE International Energy Conference and Exhibition, ENERGYCON 2012*, 293–298. https://doi.org/10.1109/EnergyCon.2012.6347770

Arenas, L. F., León, C. P. De, & Walsh, F. C. (2017). Engineering aspects of the design , construction and performance of modular redox fl ow batteries for energy storage. *Journal of Energy Storage*, *11*, 119–153. https://doi.org/10.1016/j.est.2017.02.007

Beccali, M., Cellura, M., & Mistretta, M. (2003). Decision-making in energy planning. Application of the Electre method at regional level for the diffusion of renewable energy technology. *Renewable Energy*, *28*(13), 2063–2087. https://doi.org/10.1016/S0960-1481(03)00102-2

Bhattarai, A., Wai, N., Schweiss, R., Whitehead, A., Lim, T. M., & Hng, H. H. (2017). Advanced porous electrodes with flow channels for vanadium redox flow battery. *Journal of Power Sources*, *341*, 83–90. https://doi.org/10.1016/j.jpowsour.2016.11.113

Blanc, C., Member, S., & Rufer, I. A. (2008). Multiphysics and Energetic Modeling of a Vanadium Redox Flow Battery. IEEE, *International Conference on Sustainable Energy Storage Technologies.*

Bortolin, S., Toninelli, P., Maggiolo, D., Guarnieri, M., & Del Col, D. (2015). CFD study on electrolyte distribution in redox flow batteries. *Journal of Physics: Conference Series*, *655*(November), 12049. https://doi.org/10.1088/1742-6596/655/1/012049

Brown, L. D., Neville, T. P., Jervis, R., Mason, T. J., Shearing, P. R., & Brett, D. J. L. (2016). The effect of felt compression on the performance and pressure drop of all-vanadium redox flow batteries. *Journal of Energy Storage*, *8*, 91–98. https://doi.org/10.1016/j.est.2016.10.003

Byrne, R., & Macartain, P. (1999). Energy Performance of an Operating 50 kWh Zinc-Bromide Flow Battery System. *2015 IEEE International Conference on Engineering, Technology and Innovation/ International Technology Management Conference (ICE/ITMC)*, *13*(6), 142–148. https://doi.org/10.1109/ICE.2015.7438688

Cervantes-Alcala, R., & Miranda-Hernandez, M. (2018). Flow distribution and mass transport analysis in cell geometries for redox flow batteries through computational fluid dynamics. *Journal of Applied Electrochemistry*, *online ver*(0), 1–12. https://doi.org/10.1007/s10800-018-1246-7

Chakrabarti, M. H., Brandon, N. P., Hajimolana, S. A., Tariq, F., Yufit, V., Hashim, M. A., Aravind, P. V. (2014). Application of carbon materials in redox flow batteries. *Journal of Power Sources*, *253*, 150–166. https://doi.org/10.1016/j.jpowsour.2013.12.038

Chen, D., Hickner, M. A., Agar, E., & Kumbur, E. C. (2013). Optimizing membrane thickness for vanadium redox flow batteries. *Journal of Membrane Science*, *437*, 108–113. https://doi.org/10.1016/j.memsci.2013.02.007

Chen, H., Ngoc, T., Yang, W., Tan, C., & Li, Y. (2009). Progress in electrical energy storage system : A critical review. *Progress in Natural Science*, *19*(3), 291–312. https://doi.org/10.1016/j.pnsc.2008.07.014

Conway, B. (1991). Transition from “Supercapacitor” to “Battery” Behavior in Electrochemical Energy Storage. *J. Electrochem. Soc.*, *138*(6), 1539–1548. https://doi.org/10.1149/1.2085829

Deane, J. P., Ó Gallachóir, B. P., & McKeogh, E. J. (2010). Techno-economic review of existing and new pumped hydro energy storage plant. *Renewable and Sustainable Energy Reviews*, *14*(4), 1293–1302. https://doi.org/10.1016/j.rser.2009.11.015

Dekka, A., Member, S., Ghaffari, R., Venkatesh, B., Member, S., & Wu, B. (2015). A Survey on Energy Storage Technologies in Power Systems. *2015 IEEE Electrical Power and Energy Conference (EPEC)*, 105–111. https://doi.org/10.1109/EPEC.2015.7379935

Denholm, P., Ela, E., Kirby, B., & Milligan, M. (2010). The Role of Energy Storage with Renewable Electricity Generation. *Contract*, *NREL/*(January), 1–53. https://doi.org/69

Divya, K. C., & Østergaard, J. (2009). Battery energy storage technology for power systems-An overview. *Electric Power Systems Research*, *Elsevier 79*(4), 511–520. https://doi.org/10.1016/j.epsr.2008.09.017

Duncan, R. C. (1988). World Energy Production , Population Growth , and the Road to the Olduvai Gorge, *Population and Environment*, *22*(5), 503–522.

Fedkiw, P. S., & Watts, R. W. (1984). A mathematical model for the iron/chromium redox battery. *Journal of the Electrochemical Society*, *131*(4), 701–709. https://doi.org/10.1149/1.2115676

Fisher, G. R., Ieee, M., Anstey, M. R., Viswanathan, V. V, & Perry, M. L. (2014). Redox Flow Batteries : An Engineering Perspective, *IEEE,* 102(6), 1–24.

Fujimoto, C., Zawodzinski, T., Tang, Z., Pezeshiki, A., Anderson, T., & Pratt, H. (2014). Advanced Membranes for Vanadium Redox Flow Batteries (VRB). Conference of Electricity Energy Storage Program Peer Review.

Guarnieri, M., Mattavelli, P., Petrone, G., & Spagnuolo, G. (1932). Vanadium Redox Flow Batteries: Potentials and Challenges of an Emerging Storage Technology, *IEEE Industrial Electronics Magazine* (december 2016), 10(4): 20–31.

Hadjipaschalis, I., Poullikkas, A., & Efthimiou, V. (2009). Overview of current and future energy storage technologies for electric power applications, *Elsevier*, *13*, 1513–1522. https://doi.org/10.1016/j.rser.2008.09.028

Haralambopoulos, D. A., & Polatidis, H. (2003). Renewable energy projects: structuring a multi-criteria group decision-making framework. *Renewable Energy*, *28*(6), 961–973. https://doi.org/10.1016/S0960-1481(02)00072-1

Hopkins, B. J., Smith, K. C., Slocum, A. H., & Chiang, Y. M. (2015). Component-cost and performance based comparison of flow and static batteries. *Journal of Power Sources*, *293*, 1032–1038. https://doi.org/10.1016/j.jpowsour.2015.06.023

Houser, J., Pezeshki, A., Clement, J. T., Aaron, D., & Mench, M. M. (2017). Architecture for improved mass transport and system performance in redox fl ow batteries. *Journal of Power Sources*, *351*, 96–105. https://doi.org/10.1016/j.jpowsour.2017.03.083

Huang, K.-L., Li, X., Liu, S., Tan, N., & Chen, L. (2008). Research progress of vanadium redox flow battery for energy storage in China. *Renewable Energy*, *33*(2), 186–192. https://doi.org/10.1016/j.renene.2007.05.025

Ipsakis, D., Voutetakis, S., Seferlis, P., Stergiopoulos, F., & Elmasides, C. (2009). Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage. *International Journal of Hydrogen Energy*, *34*(16), 7081–7095. https://doi.org/10.1016/j.ijhydene.2008.06.051

Jeon, D. H., Greenway, S., Shimpalee, S. Ã., & Zee, J. W. Van. (2008). The effect of serpentine flow-field designs on PEM fuel cell performance, *33*, 1052–1066. https://doi.org/10.1016/j.ijhydene.2007.11.015

Jeon, J. D., Yang, H. S., Shim, J., Kim, H. S., & Yang, J. H. (2014). Dual function of quaternary ammonium in Zn/Br redox flow battery: Capturing the bromine and lowering the charge transfer resistance. *Electrochimica Acta*, *127*, 397–402. https://doi.org/10.1016/j.electacta.2014.02.073

Jyothi Latha, T., & Jayanti, S. (2014a). Ex-situ experimental studies on serpentine flow field design for redox flow battery systems. *Journal of Power Sources*, *248*, 140–146. https://doi.org/10.1016/j.jpowsour.2013.09.084

Jyothi Latha, T., & Jayanti, S. (2014b). Hydrodynamic analysis of flow fields for redox flow battery applications Batteries. *Journal of Applied Electrochemistry*, *44*(9), 995–1006. https://doi.org/10.1007/s10800-014-0720-0

Kear, G., Shah, A. A., & Walsh, F. C. (2012). Development of the all-vanadium redox flow battery for energy storage: A review of technological, Financial and policy aspects. *International Journal of Energy Research*, *36*(11), 1105–1120. https://doi.org/10.1002/er.1863

Khor, A. C., Mohamed, M. R., Sulaimen, M. H., Daniyal, H., Razali, A. R., Oumer, A. N., & Leung, P. K. (2016). Numerical investigation on serpentine flow field and rhombus electrolyte compartment of vanadium redox flow battery (V-RFB). *ARPN Journal of Engineering and Applied Sciences*, *11*(10).

Khor, a C., Mohamed, M. R., Sulaiman, M. H., & Daud, M. R. (2014). Packaging Improvement for Unit Cell Vanadium Redox Flow Battery (V-RFB), *International Journal of Electrical, Computer, Electronics and Communication Engineering*, (6), 808–811.

Kim, D., & Jeon, J. (2015). Study on Durability and Stability of an Aqueous Electrolyte Solution for Zinc Bromide Hybrid Flow Batteries. *Journal of Physics: Conference Series*, *574*(1), 12074. https://doi.org/10.1088/1742-6596/574/1/012074

Leung, P. K., Mohamed, M. R., Shah, A. A., Xu, Q., & Conde-duran, M. B. (2015). A mixed acid based vanadium e cerium redox fl ow battery with a zero-gap serpentine architecture, *Journal of Power Sources*, *274*, 651–658. https://doi.org/10.1016/j.jpowsour.2014.10.034

Leung, P., Li, X., Leo, P. De, Berlouis, L., John, C. T., & Walsh, F. C. (2012). RSC Advances Progress in redox flow batteries , remaining challenges and their applications in energy storage. *RSC Advances*, *2*, 10125–10156. https://doi.org/10.1039/c2ra21342g

Leung, P., Palma, J., Garcia-quismondo, E., Sanz, L., Mohamed, M. R., & Anderson, M. (2016). Evaluation of electrode materials for all-copper hybrid fl ow batteries. *Journal of Power Sources*, *310*, 1–11. https://doi.org/10.1016/j.jpowsour.2015.12.069

Liu, H., Xu, Q., Yan, C., & Qiao, Y. (2011). Corrosion behavior of a positive graphite electrode in vanadium redox flow battery. *Electrochimica Acta*, *56*(24), 8783–8790. https://doi.org/10.1016/j.electacta.2011.07.083

Luo, X., Wang, J., Dooner, M., & Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, *137*, 511–536. https://doi.org/10.1016/j.apenergy.2014.09.081

Mahlia, T. M. I., Saktisahdan, T. J., Jannifar, A., Hasan, M. H., & Matseelar, H. S. C. (2014). A review of available methods and development on energy storage; Technology update. *Renewable and Sustainable Energy Reviews*, *33*, 532–545. https://doi.org/10.1016/j.rser.2014.01.068

Manders, J., Lam, L., & Peters, K. (1996). Lead/acid battery technology. *Journal of Power , 59*, 199–207. https://doi.org/10.1016/0378-7753(96)02323-3

Miyake, S., & Tokuda, N. (2001). Vanadium redox-flow battery for a variety of applications. *2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No.01CH37262)*, *1*(C), 450–451. https://doi.org/10.1109/PESS.2001.970067

Mohamed, M. R., Ahmad, H. and Abu Seman, M.N. (2012). State of the art of all-Vanadium Redox Flow Battery : A Research on research prospects. *International Review of Electrical Engineering (IREE)* 7(5): 5610-5622.

Mohamed, M. R., Ahmad, H., Seman, M. N. A., Razali, S., & Najib, M. S. (2013). Electrical circuit model of a vanadium redox flow battery using extended Kalman filter. *Journal of Power Sources*, *239*, 284–293. https://doi.org/10.1016/j.jpowsour.2013.03.127

Mohamed, M. R., Leung, P. K., Sulaiman, M. H. (2015). Performance characterization of a vanadium redox flow battery at different operating parameters under a standardized test-bed system. Applied Energy, 137, 402–412. https://doi.org/10.1016/j.apenergy.2014.10.042

Mohamed, M. R., Sharkh, S. M., Ahmad, H., Seman, M. N. A., & Walsh, F. C. (2012). Design and development of unit cell and system for vanadium redox flow batteries (V-RFB). *International Journal of the Physical Sciences*, *7*(7), 1010–1024. https://doi.org/10.5897/IJPS11.1555

Mohammadi, T. and Skyllas- Kazacos, M. (1995). Characterisation of novel composite membrane for redox flow battery applications, *Journal of Membrane Science, 98(1-2)*: 77–87.

Nair, N. K. C., & Garimella, N. (2010). Battery energy storage systems: Assessment for small-scale renewable energy integration. *Energy and Buildings*, *42*(11), 2124–2130. https://doi.org/10.1016/j.enbuild.2010.07.002

Painuly, J. P. (2001). Barriers to renewable energy penetration: A framework for analysis. *Renewable Energy*, *24*(1), 73–89. https://doi.org/10.1016/S0960-1481(00)00186-5

Parasuraman, A., Lim, T. M., Menictas, C., & Skyllas-Kazacos, M. (2013). Review of material research and development for vanadium redox flow battery applications. *Electrochimica Acta*, *101*, 27–40. https://doi.org/10.1016/j.electacta.2012.09.067

Park, D., Jeon, K., Ryu, C., & Hwang, G. (2017). Journal of Industrial and Engineering Chemistry Performance of the all-vanadium redox fl ow battery stack. *Journal of Industrial and Engineering Chemistry*, *45*, 387–390. https://doi.org/10.1016/j.jiec.2016.10.007

Pehnt, M. (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, *31*(1), 55–71. https://doi.org/10.1016/j.renene.2005.03.002

Perry, M. L., & Weber, A. Z. (2016). Advanced Redox-Flow Batteries: A Perspective. *Journal of The Electrochemical Society*, *163*(1), A5064–A5067. https://doi.org/10.1149/2.0101601jes

Ponce de León, C., Frías-Ferrer, a., González-García, J., Szánto, D. a., & Walsh, F. C. (2006). Redox flow cells for energy conversion. *Journal of Power Sources*, *160*(1), 716–732. https://doi.org/10.1016/j.jpowsour.2006.02.095

Prifti, H., Parasuraman, A., Winardi, S., Lim, T. M., & Skyllas-Kazacos, M. (2012). Membranes for redox flow battery applications. *Membranes*, *2*(2), 275–306. https://doi.org/10.3390/membranes2020275

Rahman, F., & Skyllas-Kazacos, M. (2009). Vanadium redox battery: Positive half-cell electrolyte studies. *Journal of Power Sources*, *189*(2), 1212–1219. https://doi.org/10.1016/j.jpowsour.2008.12.113

Ritchie, A., & Howard, W. (2006). Recent developments and likely advances in lithium-ion batteries. *Journal of Power Sources*, *162*(2 SPEC. ISS.), 809–812. https://doi.org/10.1016/j.jpowsour.2005.07.014

Rusllim Mohammad, M., Sharkh, S. M., & Walsh, F. C. (2010). Redox flow batteries for hybrid electric vehicles: progress and challenges. *2009 IEEE Vehicle Power and Propulsion Conference*, (August 2016), 551–557. https://doi.org/10.1109/VPPC.2009.5289801

Rychcik, M., & Skyllas-Kazacos, M. (1988). Characteristics of a new all-vanadium redox flow battery. *Journal of Power Sources*, *22*(1), 59–67. https://doi.org/10.1016/0378-7753(88)80005-3

Schaber, C., Mazza, P., & Hammerschlag, R. (2004). Utility-Scale Storage of Renewable Energy, *The Electricity Journal*, 17(6), 21-29.

Scrosati, B., & Garche, J. (2010). Lithium batteries: Status, prospects and future. *Journal of Power Sources*, *195*(9), 2419–2430. https://doi.org/10.1016/j.jpowsour.2009.11.048

Seyed Schwan Hosseiny. (2011). *Vanadium / Air Redox Flow Battery*. Faculty of Science and Technology, Membrane Science & Technology. PhD Thesis: 174

Shah, a. a., Al-Fetlawi, H., & Walsh, F. C. (2010). Dynamic modelling of hydrogen evolution effects in the all-vanadium redox flow battery. *Electrochimica Acta*, *55*(3), 1125–1139. https://doi.org/10.1016/j.electacta.2009.10.022

Shibata, T., Kumamoto, T., Nagaoka, Y., & Kawase, K. (2009). Redox Flow Batteries for the Stable Supply of Renewable Energy, *SEI Technical Review*, 14–22.

Shigematsu, T. (2011). Redox flow battery for energy storage. *SEI Technical Review*, (73), 4–13. https://doi.org/10.1149/1.3492325

Shukla, A. K., Venugopalan, S., & Hariprakash, B. (2001). Nickel-based rechargeable batteries. *Journal of Power Sources*, *100*(1–2), 125–148. https://doi.org/10.1016/S0378-7753(01)00890-4

Skyllas-Kazacos, M., Chakrabarti, M. H., Hajimolana, S. a., Mjalli, F. S., & Saleem, M. (2011). Progress in Flow Battery Research and Development. *Journal of The Electrochemical Society*, *158*(8), R55. https://doi.org/10.1149/1.3599565

Thaller, L.H. 1976. Electrically rechargeable redox flow cells. Patent, U.S. 3996064.

Tüber, K., Oedegaard, A., Hermann, M., & Hebling, C. (2004). Investigation of fractal flow-fields in portable proton exchange membrane and direct methanol fuel cells, *Journal of Power Sources, 131*, 175–181. https://doi.org/10.1016/j.jpowsour.2003.11.078

Väyrynen, A., & Salminen, J. (2012). Lithium ion battery production. *Journal of Chemical Thermodynamics*, *46*, 80–85. https://doi.org/10.1016/j.jct.2011.09.005

Verma, H., Gambhir, J., & Goyal, S. (2013). Energy Storage : A Review. *International Journal of Innovative Technology and Exploring Engineering (IJITEE)*, *3*(1), 63–69.

Weber, A. Z., Mench, M. M., Meyers, J. P., Ross, P. N., Gostick, J. T., & Liu, Q. (2011). Redox flow batteries : a review, *Journal of Applied*, 41(10), 222-348. https://doi.org/10.1007/s10800-011-0348-2

Wei, L., Zhao, T. S., Zeng, L., Zhou, X. L., & Zeng, Y. K. (2016). Copper nanoparticle-deposited graphite felt electrodes for all vanadium redox flow batteries. *Applied Energy*, *180*, 386–391. https://doi.org/10.1016/j.apenergy.2016.07.134

Winsberg, J., Hagemann, T., Janoschka, T., Hager, M. D., & Schubert, U. S. (2016). Redox-Flow Batteries: From Metals to Organic Redox-Active Materials. *Angewandte Chemie - International Edition*, 686–711. https://doi.org/10.1002/anie.201604925

Wu, X., Hu, J., Liu, J., Zhou, Q., Zhou, W., & Li, H. (2014). Ion exchange membranes for vanadium redox flow batteries. *Pure and Applied Chemistry*, *86*(5), 633–649. https://doi.org/10.1515/pac-2014-0101

Xie, Z., He, P., Du, L., Dong, F., Dai, K., & Zhang, T. (2013). Comparison of four nickel-based electrodes for hydrogen evolution reaction. *Electrochimica Acta*, *88*, 390–394. https://doi.org/10.1016/j.electacta.2012.10.057

Xu, Q., & Zhao, T. S. (2015). Fundamental models for flow batteries. *Progress in Energy and Combustion Science, Elsevier, 49*, 40–58. https://doi.org/10.1016/j.pecs.2015.02.001

Xu, Q., Zhao, T. S., & Leung, P. K. (2013). Numerical investigations of flow field designs for vanadium redox flow batteries. *Applied Energy*, *105*, 47–56. https://doi.org/10.1016/j.apenergy.2012.12.041

Xu, Q., Zhao, T. S., & Zhang, C. (2014a). Performance of a vanadium redox flow battery with and without flow fields. *Electrochimica Acta*, *142*, 61–67. https://doi.org/10.1016/j.electacta.2014.07.059

Yang, C. J., & Jackson, R. B. (2011). Opportunities and barriers to pumped-hydro energy storage in the United States. *Renewable and Sustainable Energy Reviews*, *15*(1), 839–844. https://doi.org/10.1016/j.rser.2010.09.020

Yang, H. S., Park, J. H., Ra, H. W., Jin, C. S., & Yang, J. H. (2016). Critical rate of electrolyte circulation for preventing zinc dendrite formation in a zinc-bromine redox flow battery. *Journal of Power Sources*, *325*, 446–452. https://doi.org/10.1016/j.jpowsour.2016.06.038

Yin, C., Gao, Y., Guo, S., & Tang, H. (2014). A coupled three dimensional model of vanadium redox flow battery for flow field designs. *Energy*, *74*(C), 886–895. https://doi.org/10.1016/j.energy.2014.07.066

You, D., Zhang, H., & Chen, J. (2009). A simple model for the vanadium redox battery. *Electrochimica Acta*, *54*(27), 6827–6836. https://doi.org/10.1016/j.electacta.2009.06.086

You, X., Ye, Q., & Cheng, P. (2016). Scale-up of high power density redox flow batteries by introducing interdigitated flow fields. *International Communications in Heat and Mass Transfer*, *75*, 7–12. https://doi.org/10.1016/j.icheatmasstransfer.2016.03.021

Zeng, Y. K., Zhao, T. S., An, L., Zhou, X. L., & Wei, L. (2015). A comparative study of all-vanadium and iron-chromium redox flow batteries for large-scale energy storage. *Journal of Power Sources*, *300*, 438–443. https://doi.org/10.1016/j.jpowsour.2015.09.100

Zeng, Y. K., Zhou, X. L., An, L., Wei, L., & Zhao, T. S. (2016). A high-performance flow-field structured iron-chromium redox flow battery. *Journal of Power Sources, 324,* 738–744. https://doi.org/10.1016/j.jpowsour.2016.05.138

Zhao, P., Zhang, H., Zhou, H., Chen, J., Gao, S., & Yi, B. (2006). Characteristics and performance of 10 kW class all-vanadium redox-flow battery stack, *Journal of Power Sources, 162,* 1416–1420. https://doi.org/10.1016/j.jpowsour.2006.08.016

Zhu, N., Zhang, L., Li, C., & Cai, C. (2003). Recycling of spent nickel-cadmium batteries based on bioleaching process. *Waste Management*, *23*(8), 703–708. https://doi.org/10.1016/S0956-053X(03)00068-0